GEV-TEV GALACTIC COSMIC RAYS

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Abstract. This short review aims at presenting the way we currently understand, model, and constrain the transport of cosmic rays in the GeV-TeV energy domain. This is a research field per se, but is also an important tool *e.g.* to improve our understanding of the cosmic-ray sources, of the diffuse non-thermal Galactic emissions (from radio wavelengths to gamma-rays), or in searches for dark matter annihilation signals. This review is mostly dedicated to particle physicists or more generally to non-experts.

Introduction: The theoretical grounds of cosmic-ray (CR) physics have been developed for almost 5 decades [1], but it is only since very recently that observations with sufficient precision have become available to test the main features of the models. The sources of GeV-TeV CRs are mostly by-products of supernova explosions. Supernova remnants (SNRs) and pulsar wind nebulae (PWNe) are the main Galactic CR (GCR) accelerators[b]. The former accelerate hadrons and electrons at non-relativistic shocks, whereas the latter mostly accelerate electron-positron pairs produced from the annihilation of curvature photons with the strong magnetic fields around pulsars. Though the details of the acceleration mechanisms are not completely established, direct observations of these sources in radio, X-rays or gamma-rays prove that they do accelerate CRs up to 10-100 TeV.

The transport of Galactic cosmic rays: For reviews and/or books, see [1–3] and references therein. In this section, I will introduce basic ingredients to help the non-experts understand CR transport and some degeneracies that currently plague even the most evolved models.

GCRs are charged particles that diffuse off magnetic inhomogeneities δB in the Galaxy, with typical amplitudes $\delta B/B \sim 1$ (with $B \approx \mathcal{O}(1\,\mu\text{G})$. Even though the Galactic magnetic field exhibits clear patterns in the spiral arms, these magnetic fluctuations still "isotropize" GCRs over scales of the order of a few times the Larmor radius $r_l \simeq 10^{-3}\,\text{pc} \times \{1/|Z|\,(pc/1\,\text{TeV})\,(B/1\,\mu\text{G})^{-1}\}$, much shorter than the coherence length of the regular magnetic component. Let's first forget about the specific geometry of the Milky Way (MW) and the details of CR transport. Let's focus on stable CR nuclei, and consider only two different timescales: the confinement (or escape) time τ_{esc} (magnetic confinement in the MW), and the spallation time τ_{s} (inelastic interactions with the ISM gas) — for nuclei, energy losses mostly play a role at sub-GeV energies. The former must be a decreasing function of rigidity ($\mathcal{R} \equiv p/|Z|$) because when

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[b] A PWN must be paired with an SNR (not necessarily observable), though the contrary is not true, as for type 1A SNe

r_l reaches the size of the MW, CRs are no longer confined. The latter is a much weaker function of momentum as far as nuclear cross sections are considered. We can write a simple evolution equation for the differential CR density $\mathcal{N} = dn/dp$: $\frac{d\mathcal{N}}{dt} = \mathcal{Q} - \frac{\mathcal{N}}{\tau_{\rm esc}} - \frac{\mathcal{N}}{\tau_s}$, where $\mathcal{Q}$ is a source term. We can assume that the latter is constant in time (related to the SN explosion rate) and take the steady-state limit of the above equation to link the source features to the local CR density from $\tau_{\rm esc}$ and τ_s (much smaller than the age of the Galaxy). This is the so-called leaky-box (LB) model, which allows to estimate the confinement time. Nevertheless, this requires to know the source term accurately, which we don't. This can be circumvented by considering two different kinds of CRs together: the primaries produced at sources (denoted A), and the secondaries produced only from inelastic scatterings of primaries with the ISM gas (denoted B, and assumed unique for simplicity). The source term for B is then merely $\mathcal{N}_A/\tau_{s,A}$, and using the steady state regime of the previous equation, we get: $\frac{\mathcal{N}_B}{\mathcal{N}_A} = \frac{\tau_{\rm esc}\tau_{s,B}}{(\tau_{\rm esc}+\tau_{s,B})\tau_{s,A}} \overset{\mathcal{R}\nearrow\nearrow}{\approx} \frac{\tau_{\rm esc}(\mathcal{R})}{\tau_{s,A}}$, where the last approximation is obtained from the different rigidity dependences of $\tau_{\rm esc}$ and $\tau_{s,B}$, for large $\mathcal{R}$ (this can be checked *a posteriori*, taking $1/\tau_{s,B} = \sigma_B\, v\, \bar{n}_{\rm ism}$, where σ_B is the $B + {\rm ISM} \to X$ cross section and $\bar{n}_{\rm ism} < n_{\rm ism}$ is the average ISM gas density encountered by a CR while it is confined). Therefore the secondary-to-primary (II/I) ratio, as derived in the LB model, allows to determine the energy dependence of $\tau_{\rm esc}$. For its amplitude, one needs to refine the description of the spallation timescales by considering more elaborated distribution functions for the grammage (the column-density equivalent for CRs propagating in the ISM). The most widely used II/I ratio is the boron-to-carbon (B/C) because it is best measured. One typically finds a good fit to the data by taking $\tau_{\rm esc} = \tau^0_{\rm esc}(\mathcal{R}/1\,{\rm GV})^{-\delta}$, with $\tau^0_{\rm esc} \approx 100$ Myr and $\delta \approx 0.3$-0.5 (for kinetic energies above 1 GeV/nucleon).

We can now improve the physical picture by considering diffusion. It is a much involved theoretical field to try to infer the diffusion properties from those of magnetic turbulences, but we can first assume that the magnetic scatterers are distributed homogeneously in an extended slab that encompasses the Galactic disk, and that the diffusion coefficient is a scalar function of the rigidity $K(\mathcal{R})$. The former is motivated by *e.g.* radio observations of the MW and of external disk galaxies. This slab has a half-height L, unknown *a priori*, but expected to be much larger than that of the disk, $h \simeq 100$ pc. Assuming that the ISM gas is confined to an infinitely thin disk ($h \ll L$), we may write for a stable CR species: $\partial_t\mathcal{N} - \vec{\nabla}(K(\mathcal{R})\vec{\nabla}\mathcal{N}) + 2\,h\,n_{\rm ism}\,\delta(z)\,\sigma\,v\,\mathcal{N} = \mathcal{Q}$, where σ is the spallation cross section. For simplicity, we assume the slab radially extends to infinity. This reduces the above equation to one spatial coordinate z, perpendicular to the disk. We take the steady-state limit, and, to account for the escape, demand that $\mathcal{N}(|z| = L) = 0$. For primary as well as secondary astrophysical CRs, the source term is confined to the disk, such that we may assume that $\mathcal{Q} = 2\,h\,\delta(z)\,\mathcal{Q}_0(\mathcal{R})$. For $z \neq 0$, a solution satisfying the boundary conditions is given by $\mathcal{N}(z \neq 0) = \mathcal{N}(0)(1 - |z|/L)$. By integrating the previous equation in the range $[-\epsilon, +\epsilon]$ in the limit $\epsilon \to 0$ ($\epsilon > 0$), we get: $\frac{K}{h\,L}\mathcal{N}(0) + n_{\rm ism}\,\sigma\,v\,\mathcal{N}(0) = \mathcal{Q}_0$. By analogy with the LB equation, one can readily conclude that the II/I ratios allow us to constrain $K/L \propto 1/\tau_{\rm esc} \propto \mathcal{R}^\delta$. This suggests that $K(\mathcal{R}) = K_0\,(\mathcal{R}/1\,{\rm GV})^\delta$ provides a good description of the data — typical values are $K_0 \sim 0.01$ kpc^2/Myr and $\delta \sim 0.3$-0.5. Such a power-law shape for the diffusion coefficient is actually supported independently by theoretical results, in case diffusion originates from magnetic turbulence with a power-law spectrum (which is widely encountered in hydrodynamic systems) — an idealized example is the Kolmogorov turbulence spectrum, for which δ is close to 1/3. Note that a full theory connecting any turbulence properties to diffusion is yet to be derived, but models exist and can be tested [4].

An important consequence of the above result is that the normalization of the diffusion coefficient K_0 and the slab size L, both unknown *a priori*, are found degenerate in the II/I ratio ($K/L \propto 1/\tau_{\rm esc}$). Since we have seen from the LB model that the primary source term cancels out in the ratio, it is not surprising that any *prediction* made for other astrophysical secondary species from a primary spectrum should not be affected by uncertainties in K_0 and L, provided the K_0/L is fixed. This remains roughly valid in any diffusion model, because the source terms for primary as well as secondary CRs originate in the Galactic disk. This is no longer the case for CRs that would be produced in the whole magnetic halo; a constant source term would then give $\mathcal{N}(0) \stackrel{\sim}{\propto} L^2/K$: any prediction made for such a case is therefore very sensitive to L. This is typical of what happens for antimatter flux predictions made for dark matter signals, while the so-called secondary background prediction is under control (except for positrons, see below). Indeed, from the II/I ratios only, L can typically range from 1 to 15 kpc [5].

This $K_0 - L$ degeneracy is rather endemic of all CR diffusion models, but, fortunately, there are ways to break it, based on two different approaches: (i) probe physical observables which are not sensitive to the spatial boundary L; (ii) probe physical observables that exhibit non-linear dependences on K_0 and L. For case (i), on may use unstable (radioactive) secondary CRs with decay timescales τ_0 such that the associated diffusion scalelength is $\lambda_{\rm d} \sim \sqrt{K\,\gamma\,\tau_0} \ll L$, beyond which contributions are suppressed. One can therefore only observe those unstable CRs which have been produced within a distance $\sim \lambda_{\rm d}$. The most used CR "clocks" range from $\tau_0 = 0.301$ Myr (^{36}Cl) to 1.36 Myr (^{10}Be), for which, assuming a kinetic energy of 1 GeV/nucleon one finds $\lambda_{\rm d}$ ranging from 100 to 240 pc. Using such constraints, the available data strongly favor large-halo models, with $L > 5$ kpc [3]. Nevertheless, there are two important drawbacks. First, measuring fluxes of radioactive species is very challenging, and current data have large error bars (AMS02 should improve). Second, the fact that $\lambda_{\rm d} \sim 200$ pc implies that this method is very sensitive to the details of the local ISM, and there are hints that the local ISM is underdense over a scale of $\sim$ 100 pc (known as the *local bubble*). Therefore, this procedure could be affected by large systematic errors [6, 7]. As for case (ii), different observables can be used. Studies based on predictions of the diffuse Galactic gamma-ray emission [8] (see I. Moskalenko's contribution in these proceedings), and of the diffuse Galactic radio emission [9], strongly favor values of $L > 5$ kpc. In both cases, this comes from the contribution of CR electrons (gamma-rays from inverse Compton on CMB outside the disk, radio from synchrotron losses). Nevertheless, these are indirect constraints which also strongly depend on the descriptions of the radiation fields in the disk and of the magnetic field. More direct constraints come from the local secondary positron flux at low energy, for which small values of K_0 lead to predictions in excess with respect to the data (the correlation with L induced by the II/I ratios implies strong constraints on small values of L). This is clear from the predictions made in [10,11], and was pointed out in the context of dark matter searches [12].

State-of-the-Art: Evolved CR transport models include more ingredients than those discussed above. They generally rely on the following general CR transport equation (and then may differ in the assumptions used to solve it): $\partial_t \mathcal{N} - \vec{\nabla} \cdot \left\{ \left[K_x \, \vec{\nabla} - \vec{V}_c \right] \mathcal{N} \right\} + \partial_p \left\{ \left[\dot{p} - \frac{p}{3} \vec{\nabla} \cdot \vec{V}_c - p^2 K_p \partial_p \frac{1}{p^2} \right] \mathcal{N} \right\} + \left[\frac{1}{\tau_s(\vec{x},p)} + \frac{1}{\tau_{\rm dec}(p)} \right] \mathcal{N} = \mathcal{Q}$. New ingredients have appeared: the convection velocity $\vec{V}_c$ that encodes the effect of stellar winds in the disk; the energy loss term $\dot{p}$ (a spatial dependence is implicit), which is very important for the transport of electrons and positrons (inverse Compton and synchrotron losses dominate above a few GeV); reacceleration, through a diffusion coefficient in momentum space K_p, predicted to be related to spatial diffusion by the relation $K_x K_p \propto p^2 V_a^2$, where V_a is the average velocity of the magnetic scatterers (*i.e.* the Alfvèn velocity in some idealized cases); the decay and spallation timescales $\tau_{\rm dec}$, τ_s, which only affect nuclei (radioactive nuclei for the former).

These parameters may be theoretically constrained, like $K_x(\mathcal{R}) \propto \mathcal{R}^\delta$, but hardly be fully inferred from first principles (except for the cross sections), as they often result from large-scale averages of complex microphysics that depends on the details of many Galactic components. In particle physics language, this is an effective theory. All parameters have to be calibrated from observational data (mostly II/I, but also diffuse emissions). Depending on the assumptions, the above transport equation can be solved semi-analytically or fully numerically. The former method (*e.g.* [5,7,13]) is well suited to study theoretical uncertainties, while the latter (*e.g.* the popular Galprop code [14] or derivatives), more CPU-time demanding, is often used to probe more complex configurations of the different input parameters or observables (*e.g.* implement more detailed source/gas distributions for diffuse gamma-ray predictions).

The present generation of CR experiments have reached sensitivities that push the most popular transport models to their limits, as the predictions get more and more sensitive to the theoretical assumptions or prejudice. Though critical for data interpretations, this is good news for CR theorists.

Some issues related to cosmic-ray transport: In this section, as a conclusion to this contribution, I briefly review some issues related to cosmic-ray transport.

The rising positron fraction: In 2009, the PAMELA data [15] confirmed with clear statistical significance previous indications [16] that the positron fraction ($\phi_{e^+}/(\phi_{e^+}+\phi_{e^-})$) was increasing with energy, in contrast with what is expected when assuming CR positrons are pure secondaries [10, 11, 17]: there must be sources of primary positrons (AMS02 confirmed this rise [18] up to a flattening at energies around 350 GeV). It has actually been known for decades that pulsars are sources of electron-positron pairs that are further accelerated in PWNe [19]. Moreover, at energies beyond 10 GeV, the discreteness of the source distribution becomes manifest for CR electrons and positrons, and one has to account for the known local objects [20]. This is because of energy losses $b(E) = -dE/dt \propto E^2$, which imply that the spatial horizon λ of positrons decreases with energy ($\lambda^2 \approx K(E)\,E/b(E)$), down to ~ 1 kpc for $\gtrsim$100 GeV. Therefore, PWNe are natural candidates to explain the increase of the positron fraction [21]. Nevertheless, a detailed and constrained dynamical modeling of these local sources is still lacking (chi-square analyses relying on simplistic descriptions are no longer sufficient). Another interesting astrophysical scenario relies on the possibility that this increase be due to secondary positrons produced in SNRs and accelerated *in situ* at non-relativistic shocks [22]; this scenario also predicts increases in other II/I ratios ($\bar{\mathrm{p}}$/p, B/C), which will be tested very soon with AMS02. Finally, a more speculative source of positrons is dark matter annihilation or decay [23,24], while this would require unconventionally large annihilation or decay rates and very fine-tuned scenarios. Though this can formally not be excluded from present astrophysical knowledge, the very existence of astrophysical sources precludes the positron data from being interpreted as a clean dark matter signal, and one can at best use the data to put constraints [25]. Solutions to the rising positron fraction illustrate that an accurate (local) description of the spatial source distribution is a critical ingredient for predictions related to high-energy CR electrons and positrons. This also holds for inverse Compton predictions.

Puzzles at the Galactic center (GC): Recently, many gamma-ray excesses have been reported toward the GC, where CR physics is fundamental for interpretation or criticism (contributions from hadronic or inverse Compton - leptonic - processes). Three cases: (i) the Fermi bubbles [26], (ii) the 130 GeV gamma-ray line [27], (iii) 10-50 GeV "excess" at the GC [28]. Case (i) is observationally established (large-scale gamma-ray emission around the GC), and interpretation mostly relies on CR acceleration and transport, with both hadronic and leptonic scenarios [29–31], or astrophysical jet physics. What is interesting with these features is that they challenge the idea that CR transport could be described everywhere assuming a simplistic slab geometry wherein the diffusion coefficient would be homogeneous (the bubbles extend up to 8 kpc away from the GC). Though not firm detections, cases (ii) and (iii) are interesting in the sense that their putative interpretations depend on diffuse gamma-ray background models (both the intensity and the spectral shape), and thereby on CRs (sources, transport, and ISM at the GC). I hope it is clear from above that uncertainties are large even at the stage of modeling. It is therefore not surprising at first sight to find observational departures from current background models, even though a gamma-ray line, if detected at high significance, would be difficult to associate with a CR origin. Anyway, strong theoretical and modeling improvements will be necessary to fully understand the high-energy phenomena at the GC in the near future. This is a very active research field.

Spatial diffusion and reacceleration: To conclude, I emphasize that most CR transport models rely on the assumption that the spatial diffusion coefficient is homogeneous and isotropic in a slab, and has a power-law dependence on rigidity. Such approximations are sufficient to get a consistent physical picture for what concerns CR nuclei, but some problems remain unsolved. For instance, II/I data seem to prefer values of the power-law slope of the diffusion coefficient which are in significant tension with the absence of anisotropy [32]. Understanding the intimate relations between the magnetic turbulence existing in astrophysical environments and the diffusion properties of CRs is a therefore promising line of research for the near future [4, 33]. To some extent, this will affect the interpretation of the rising positron fraction (diffusion a in very local environment), as well as that of any other fine-structure observation (*e.g.* the GC, or features in the diffuse gamma-ray emission). Finally, since reacceleration is linked to diffusion and strongly affects the sub-GeV CR budget (and fits to the II/I data), more systematic theoretical inspections are now necessary [34]. Current and new generations of multiwavelength observations and CR experiments will bring important matter to the field in the next decade.

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